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Controlling the Startup Modes of Cogeneration Steam Turbines Operating as Part of Combined-Cycle Power Plants

V. N. Goloshumova[a, b], Yu. M. Brodov[a], I. Yu. Klyainrok[a, b], and A. A. Smirnov[a]

[a] *Ural Turbine Works, ul. Frontovykh Brigad 18, Yekaterinburg, 620017 Russia*

[b] *Ural Federal University, ul. Mira 19, Yekaterinburg, 620002 Russia*

Abstract—The results obtained from investigations of combined-cycle power plants produced by the Ural Turbine Works aimed at achieving high maneuverability, reliability and longevity of cogeneration steam turbines taking into consideration the possibilities of modern automated process control systems are presented. The dynamic models for simulating the heating of a steam turbine cylinder's parts with the use of limited computation capacities are developed.

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Specialists of the Ural Turbine Works (UTZ), working jointly with specialists of the Ural Federal University's (UrFU) Department of Turbines and Engines, carry out works on achieving high maneuverability, reliability, and longevity of cogeneration steam turbines (STs) through setting up in-depth monitoring and control of equipment parameters [1], due to which lower probability of errors that can potentially be committed by the operating personnel should be achieved.

UTZ specialists have developed projects of combined-cycle power plants (CCPs) for cogeneration stations equipped with a heat-recovery boiler (CCP-based CSs with an HRB) and for CCP-based CSs with a parallel process scheme. For the cogeneration steam turbines operating as part of CCPs produced by UTZ the authors develop the technological principles of a system for automated control of startup operations taking into account the modern possibilities of automated process control systems (APCSs) in which efficient control algorithms are implemented using microprocessor devices. It should be noted that certain works should be carried out for each family of cogeneration steam turbines operating as part of a CCP (their interconnection is shown in Fig. 1 [2]):

—studying the temperature and thermally stressed state of the main structural elements of a cogeneration steam turbine;

—revealing the most thermally stressed elements of a cogeneration steam turbine and selecting the critical one among them;

—working out design measures for achieving better maneuverability of equipment;

—working out software for microprocessor devices; and

—setting up real-time monitoring of the temperature and thermally stressed state of the critical element (individually for each family of cogeneration steam turbines used as part of a CCP).

This paper presents the results obtained from an investigation carried out as applied to the CCPs produced by UTZ in accordance with the above-mentioned top-priority works.

The time taken to start a CCP is primarily governed by the time required for starting the steam turbine [3], which in turn depends on the thermally stressed state of its parts. The highest temperature stresses arise in the high-pressure rotor (HPR), in the intermediate-pressure rotor of turbines with steam reheating, in the casing of the high-pressure cylinder, and in the stop valves. The data used as input information for microprocessor computing devices include directly measured parameters such as rotor rotation frequency, steam turbine power output, steam temperatures, and the casing metal temperature of the high- and intermediate-pressure cylinders (HPC and IPC). The output information produced by these devices is the difference of temperatures or stress in the critical (i.e., the most stressed) zone of the critical part. In starting a turbine, it is advisable to maintain the difference of temperatures (stresses) in the critical elements at the maximum permissible level; as regards the other reliability criteria, they must not exceed the permissible (regulated) values.

The cogeneration steam turbines for CCP-based CSs with HRBs designed by UTZ [4–6] use an all-forged high-pressure rotor. Throttle steam admission in combination with independent control of the high-, low-, and (if any) intermediate-pressure stop and control valves is used in all loops through which steam is supplied to the turbine. The high-pressure rotor does not contain a control stage. The HPC consists of standardized parts. If the HPC has a cast-and-welded design, the casing of the high-pressure part is made by casting and has a design similar to the casing of the

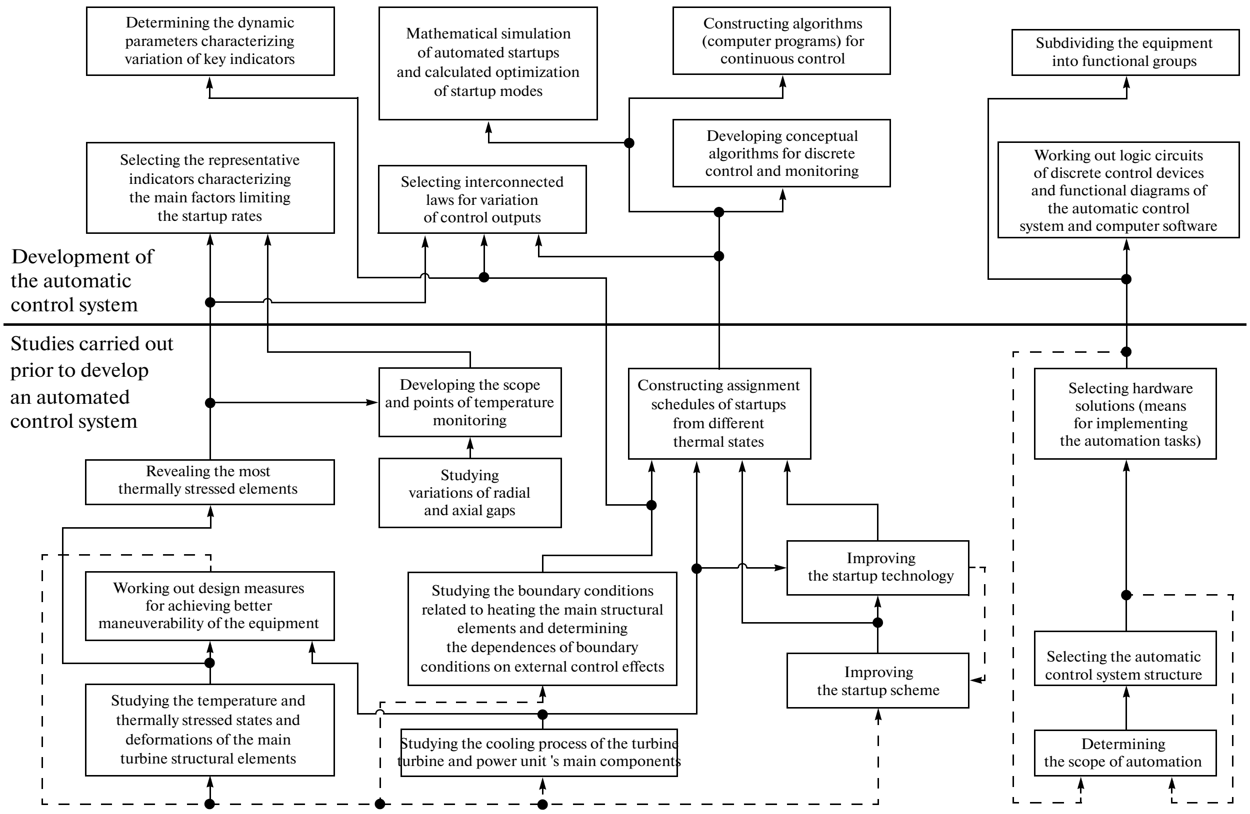


Fig. 1. Structure of top-priority investigations to be carried out prior to organize automated startup modes of the cogeneration steam turbines used as part of CCPs.

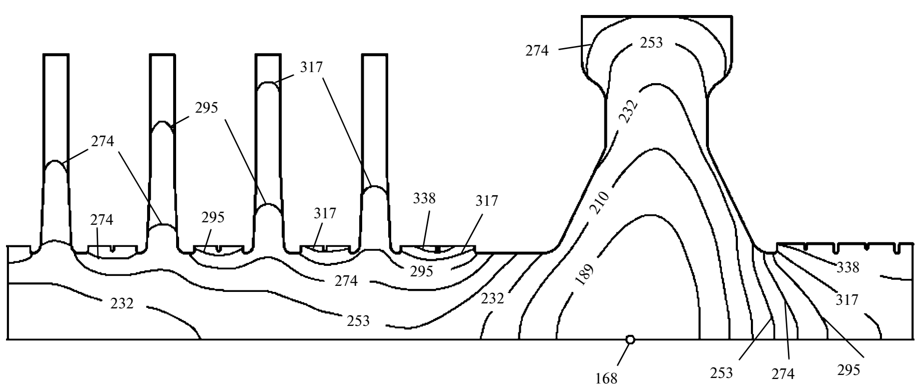


Fig. 2. Temperature field (°C) of the high-pressure rotor of a T-110 turbine during its startup from cold state 20 min after kicking the rotor.

PT-30/35-8.8/0.98-5 turbine. If the HPC has a cast design, its casing has a design similar to the casing of the serially produced T-110/120-12.8 turbine (referred to henceforth as a T-110 turbine).

In [7–9], the stressed and strain state (SSS) the high-temperature parts of the T-110 turbine have in startup modes was analyzed taking into account the real geometrical configuration of the parts and with detailed specification of initial and boundary conditions (corresponding to each startup operation in the startup schedule). The critical elements and critical zones in the HPC were determined.

A critical zone was revealed for the high-pressure rotor (Fig. 2). It has been found that in the turbine startup modes, the maximum of temperature stresses is observed not in the heated bore, but in the inner bore under the control stage disk (σ_θ^{max} = 280 MPa are tensile tangential stresses). In our opinion, this phenomenon is caused by a large so-called cold spot under the

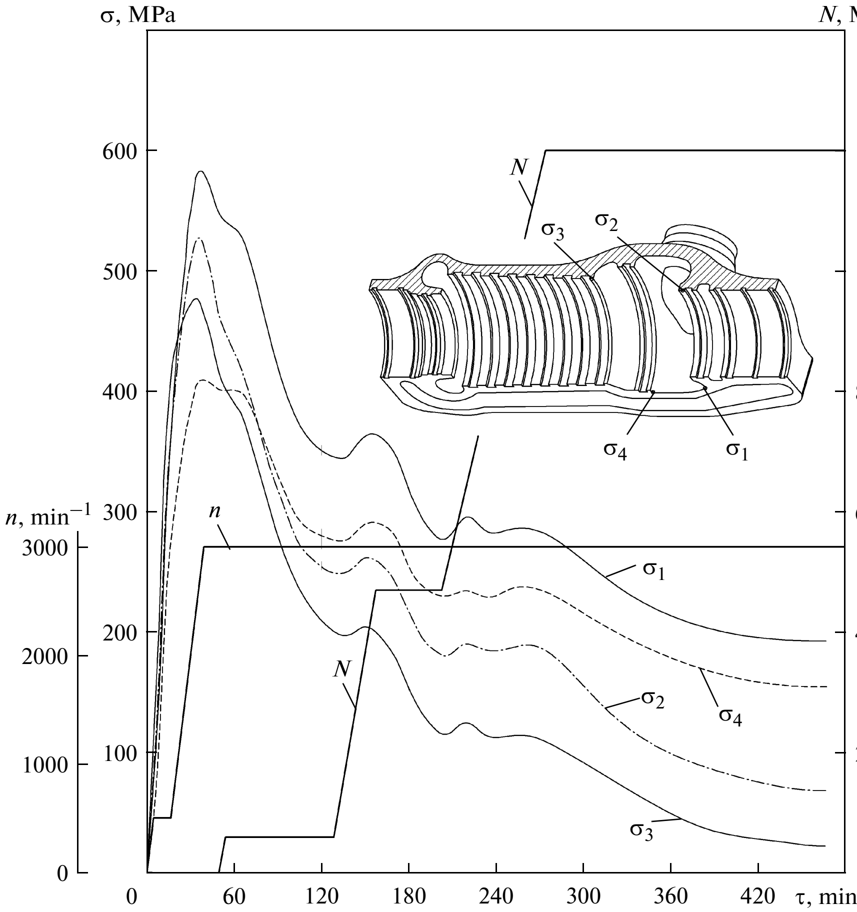


Fig. 3. Variations of conditionally elastic temperature stresses in different zones of the casing of the T-110 turbine during its startup from cold state in accordance with the startup schedule specified by UTZ. Stresses: σ_1—in the zone of the horizontal joint downstream of the nozzle box, σ_2—upstream of the front end seal's first cage, σ_3—upstream of the second-stage diaphragm, and σ_4—in the zone of the horizontal joint upstream of the guide vane cage. N is the turbine power output, and n is the rotor rotation frequency.

bulky disk of a two-bucket control stage. It should be noted that the zone of maximal temperature stresses coincides with the zone of stresses caused by centrifugal force. The equivalent temperature stresses in the rotor reach their maximal values $\sigma^{\max} = 347$ MPa at the temperature in the control stage zone $t = 300°C$ (i.e., at the initial stage of the startup process). However, these stresses do not exceed the yield stress of the rotor material $\sigma_{0.2}^{t=300°C} = 475$ MPa. In our opinion, the solution in which the high-pressure rotor of a steam turbine for a CCP is made without a two-bucket control stage opens considerable possibilities for increasing the turbine loading rate.

The stressed and strain state of the T-110 turbine's HPC casing was calculated (Fig. 3), and it was shown from that calculation that the temperature stresses σ_3 on the surfaces of the control stage chamber upstream of the second-stage diaphragm are due to rapid heating of the narrow collar unlike the wall with the casing flange. We believe that the same factor is responsible for an increased level of stresses σ_1 and σ_2 upstream of the first cage of the front end seal and in the zone of horizontal joint behind the nozzle box. The temperature stresses σ_4 in the zone of the cylinder's horizontal joint in the radial transition before the protrusion for the bore of the control stage guide vane are mainly due to the temperature differences over the flange width and height, which predetermine the occurrence of considerable stresses in this zone.

It is obvious that in the case considered, stresses can be reduced only by changing the casing cast design. One version of retrofitting the HPC casing of a T-110 turbine has been implemented in the T-53/67-8.0 turbine (referred to henceforth as a T-53 turbine) used as part of the PGU-230 combined-cycle plant at the Minsk TETs-3 cogeneration station.

As a further development of works [7–9], the critical element and the critical zone in this element were determined for the T-53 turbine used as part of the PGU-230 combined-cycle plant at the Minsk TETs-3 cogeneration station [5] (this turbine is used as a basic one in serially developed projects of CCPs for other

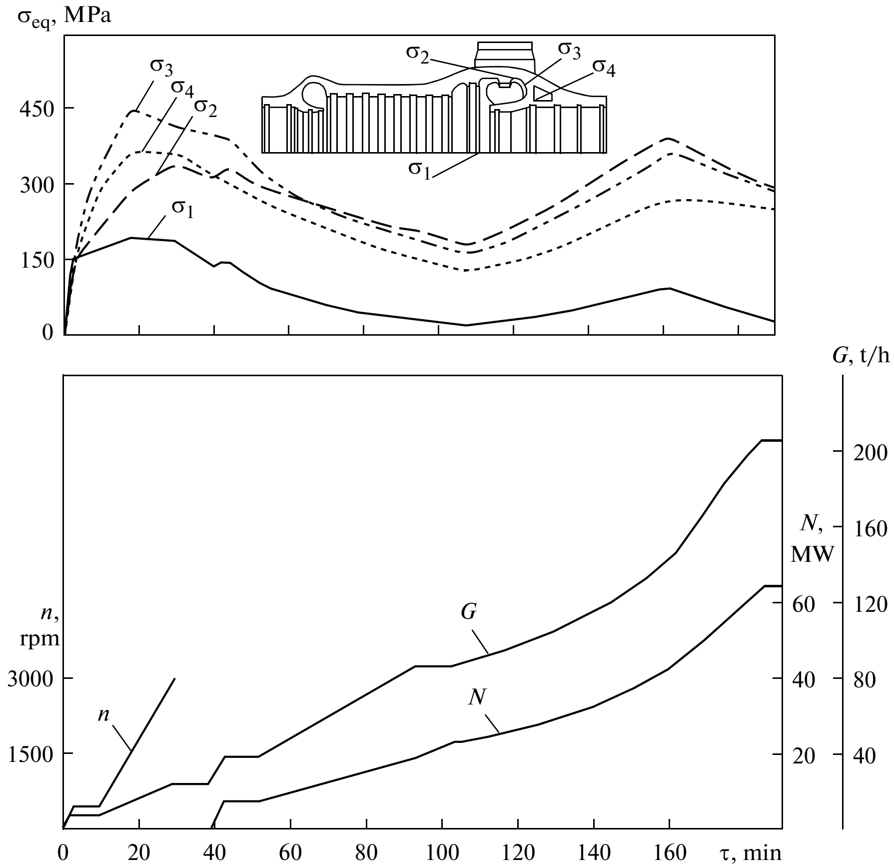


Fig. 4. Calculated variations of equivalent stresses in the high-pressure rotor of the T-53 turbine for a PGU-230 combined-cycle plant during the startup from cold state in accordance with the schedule specified by UTZ. Stresses: σ_1—in the sealing belt zone of the cylinder shell's horizontal joint, σ_2—in the steam admission zone in the radius transition segment, σ_3—in the zone of welding the Γ-shaped half-ring to the turbine casing, and σ_4—in the zone of welding the G-shaped half-ring to the steam suction chamber downstream of the front end seal's first compartment. *G* is the steam flowrate.

power stations). It has been found that the HPC casing is the critical element of the T-53 steam turbine. The curves in Fig. 4 represent calculated variations of equivalent stresses in the zones where the maximal temperature stresses occur in the HPC casing of the T-53 turbine during its startup from cold state in accordance with the schedule specified by the Ural Turbine Works (UTZ).

During the turbine speeding up stage, the zone in which the Γ-shaped half-ring is welded to the turbine casing is the most thermally stressed section of the HPC casing. By the 18th minute of the startup process, the maximal temperature stresses $\sigma_3 = \sigma_{eqv}^{max} =$ 457 MPa arise in this zone. This takes place because steam flows over the half-ring walls both from inside and outside, due to which they are heated quite rapidly unlike the wall and flanges of the casing to which the half-ring is welded. By the 60th minute of startup, the stresses in the steam admission zone in the radius transition segment (Fig. 5, zone *A*) σ_2 reach the level σ_3 and become the maximal ones ($\sigma_2 = 394$ MPa at the 162nd minute).

In our study, for continuously monitoring the thermally stressed state of the HPC casing of the T-53 turbine, we adopted a stochastic relation between the temperature stresses in zone *A* and temperature differences across the wall width ($\Delta t_w = t_1 - t_2$) and along the casing axis ($\Delta t_{ax} = t_1 - t_3$). As a result, the following regression dependence for calculating temperature stresses in zone *A* was obtained:

$$\sigma_{reg}^{A} = \beta_0 + \beta_1 \Delta t_w + \beta_2 \Delta t_{ax} + \beta_3 \Delta t_w^2 + \beta_4 \Delta t_{ax}^2 + \beta_5 \Delta t_w \Delta t_{ax},$$

where β_0 is the absolute term of the equation, and β_1–β_5 are the influence coefficients of temperature field components.

This dependence involves metal temperatures with due regard to the fact that the sensors are placed at a distance of around 10 mm from the casing wall's inner surface. In this case, the above-mentioned coefficients have the following values: $\beta_0 = -32.227$; $\beta_1 = 14.183$; $\beta_2 = 1.629$; $\beta_3 = -0.198$; $\beta_4 = -0.0002$; $\beta_5 = -0.002$. The determination coefficient of the obtained polynomial is $R^2 = 96.4\%$.

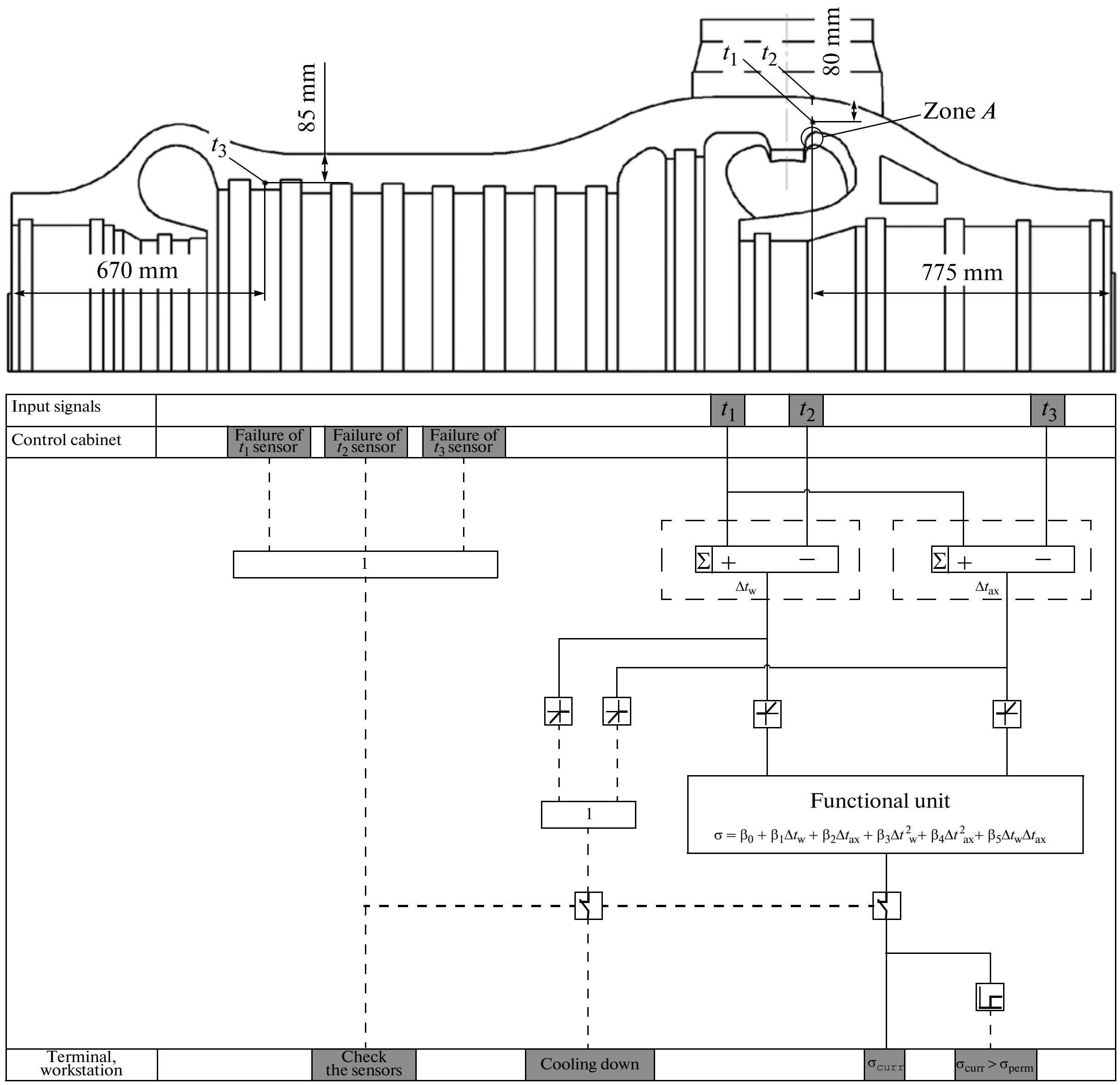
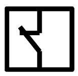
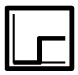
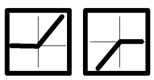
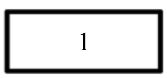
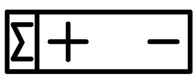


Fig. 5. Layout of thermocouples and the module for calculating temperature stresses in the steam turbine cylinder's casing.

A comparison between the temperature stresses in zone *A* found from the regression dependence and obtained from the SSS calculation showed that the maximal error of their calculation for the initial database did not exceed 20% [10, 11]. In addition, the proposed dependence is fairly simple and does not require high computation capacities for carrying out the calculations. Figure 5 shows the module for calculating temperature stresses in zone *A* of the HPC casing used in the T-53 turbine. The language for describing a requirements specification for the UTZ algorithms consists of a set of traditional logic operators, elements of relay and contact circuits, and designations adopted in the design process. We believe that for setting up continuous monitoring of the HPC casing, it is sufficient to install three sensors for metal temperature measurements as is shown in Fig. 5. The table presents the list of graphic elements used for describing the considered module.

The projects of CCP-based cogeneration stations with a parallel process scheme developed by UTZ specialists are intended for modernizing cogeneration stations [12]. The cogeneration steam turbines applied in such projects are usually made with nozzle steam admission, and the high-pressure rotor is designed with a control stage. The list of critical elements of a T-250/300-240 turbine for supercritical steam conditions and with steam reheating includes the high-pressure rotor and the first intermediate-pressure rotor (IPR-1); in cogeneration steam turbines for subcritical steam conditions this list includes the high-pres-

Graphic elements used for describing the temperature stress calculation module

Symbol	Description
	Analog signal—a signal the value of which changes continuously with time; analog signals are used for transmitting data by continuously varying their amplitude, frequency, or phase with time
	Discrete signal—a signal having a finite number of values
	**Normally closed switch**—a switch conducting current without applying the control voltage
	**Upper threshold element**—a device that produces a signal at its output when the input signal exceeds certain level called the upper actuation threshold
	**Positive/negative threshold element**—a device producing the signal at its output only when the input signal is greater/less than zero
	**Logic OR operator**—a device that produces the signal at its output when one or more signals (conditions) are applied to its input
	**Adder**—a device converting analog or digital signals into a signal equal to the sum of these signals

sure rotor if the HPC of these turbines has a uniflow scheme of steam motion in the flow path and if the high-pressure rotor has a two-bucket control stage (turbines of the T-110 family).

It is more difficult to set up monitoring of the thermally stressed state of rotors than the casing. Since direct temperature measurements of rotor metal involve certain difficulties, the metal temperature is usually determined by means of mathematical models simulating the rotor heating process in real time [13].

A one-dimension model provides a fairly accurate description of the temperature field in the critical zone of rotors, which locates in areas zones of intermediate seals of the inner casing of cylinders with a loop-type scheme of steam flow in the flow path. The use of a 1D model for the rotors of cylinders with a uniflow scheme of steam motion is hardly possible.

In [14] its authors present the results from development of a dynamic model for simulating the heating process in the critical zone of the rotor suitable for use on a computer with limited capacities. A procedure is proposed for calculating the numerical values of the functions of geometrical coordinates, namely, the position functions $P_\nu(\rho, u)$, where (ρ, u are the dimensionless radius and axial coordinate, based on calculations of the stressed and strain state of a rotor using the ANSYS software system [15]. The procedure involves detailed simulation of the full geometry of the rotors with thermal grooves, disks with fillets, and steam turbine startup schedules (for specifying the initial and boundary conditions in each characteristic segment of the rotors corresponding to each startup operation). The functions $P_\nu(\rho, u)$ are calculated with any required accuracy at the stage of developing the rotor heating model. The dynamic model involves three to four values of the functions $P_\nu(\rho, u)$ at particular points of the rotor in the form of numerical coefficients.

The position functions $P_\nu(\rho, u)$ are obtained as the solutions of the system of recurrent differential equations

$$\nabla^2 P_0(\rho, u) = 0;\quad \nabla^2 P_\nu(\rho, u) = P_{\nu-1}(\rho, u);\quad \nu \ge 1.$$

In this study, the rotor temperature field is represented as the sum of products of the position function at the characteristic points and the derivatives of the functions of external effects $y^\nu(\tau) = \dfrac{d^\nu y(\tau)}{d\tau^\nu}$ where τ is time.

The corresponding expressions have the form:

$$t(\rho, u, \tau) = \sum_{j\ge1}^{2}\sum_{\nu\ge0}^{m} y_j(\tau) P_\nu(\rho, u),\ j = 1, 2;\quad \nu = 0;\quad m = 3, 4.$$

The reason why two functions $y_1(\tau)$ and $y_2(\tau)$ are used is because the rotor heating process is governed by two independent external effects: the temperature of heating steam and its flowrate. The steam flowrate determines the coefficient of heat transfer (the Biot number) from steam to the rotor surface. The functions $y_1(\tau)$ and $y_2(\tau)$ are approximated by a dependence of the form $z = f(n, N)$.

The proposed approach allowed us to obtain relations describing the analog rotor heating model suitable for use in real-time applications.

In our study we also proposed an alternative approach; namely, a dynamical model of heating the critical zone of a rotor suitable for being implemented on a computer with limited capacities has been developed; solution of an axially symmetrical problem of unsteady heat conductance using the finite element method constitutes the physico-mathematical heart of this model. In our opinion, this approach has the following advantages (possibilities) as compared with the procedure described in [14]: the model produces comprehensive information on the rotor temperature field in the critical zone; the approach features a high degree of automation and unification in constructing the models of rotors for different turbines; and it is relatively easy to build the model into the existing loops of the power unit's automated process control system.

The MATLAB software package was chosen as a tool for implementing the dynamic model [16]. Its main advantages are as follows: it has an open and well-documented source code; it is furnished with a powerful high-level mathematical programming language; and it involves the possibility to generate the source code in the C language, which is necessary for subsequent implementation of the model. The most essential limitations for implementing the finite-element method in the MATLAB package is that only a triangle mesh with first-order approximation can be used, and that the class of problems being solved is restricted to two spatial dimensions. To check how adequately heat conductance problems are solved by means of the MATLAB system, a comparative analysis with the ANSYS software system was carried out on the well-known problems of steady and unsteady heat conductance. The solution was carried out on computation meshes generated in ANSYS and MATLAB, and also on meshes imported into MATLAB from ANSYS.

The following conclusions were drawn based on the results of the performed analysis: for problems of steady and linear unsteady heat conductance formulated in 2D statement and solved on triangular meshes, the accuracy of the solution obtained using the MATLAB computer program corresponds to the accuracy of the solution obtained in the ANSYS computer program, and the mesh generator used in MATLAB is slightly inferior to that in ANSYS both in the mesh quality indicators and in the accuracy of results obtained on the mesh.

The obtained dynamic model was simulated in the MATLAB Simulink environment. The computation mesh was generated and imported from the ANSYS computer program and contained 4219 nodes and 8046 PLANE55 elements. Since the finite-element model is linear, the problem was integrated in time using a single-step method according to the Crank–Nicholson scheme (the second order of accuracy) with a constant step equal to 15 s. In simulating the problem on a PC (with the Intel Pentium 4 processor running with a clock frequency of 2.8 GHz and with 2048 MB RAM) in the MATLAB system, the maximal time taken to calculate one step of solution was 0.7 s. This time includes the additional increase of the calculation time due to work of the operating system in the multitask mode and also due to operation of the MATLAB system in the code interpretation mode (this increase of computation time will not take place if the model is implemented on a microcontroller). The obtained temperature field in the critical zone of the rotor differs from its benchmark values by 5%.

The dynamic model of heating the control stage region of a T-110 steam turbine implemented in the MATLAB Simulink environment consists of nine blocks (Fig. 6):

Loading curve for T-110 is a signal builder reproducing startup schedules according to the operation manual.

Convection parameters for T-110 converts the output signals of the preceding block (rotor rotation frequency and turbine power output) into the parameters of convective heat transfer in the flow path in the control stage region.

BC collector for T-110 calculates the coefficients in the generalized Neuman boundary conditions.

Material model for P2MA is a model of thermophysical properties for rotor material (Grade P2MA steel); the properties are specified in tabular form as a function of metal temperature and are calculated using the piecewise-linear interpolation method.

Load mesh automatically downloads the computation mesh from the specified file immediately prior to start simulation and is necessary for correct operation of other blocks.

Discrete FEM solver runs the finite-element model downloaded by the preceding block. It operates in discrete time and integrates the system of ordinary differential equations characteristic for the finite element method using a first-order method (the Euler scheme) or a second-order method (the Crank–Nicholson scheme). In addition, the parameter window of this block is used for specifying the initial temperature of rotor metal and the model symmetry axis for axially symmetrical bodies (in the case considered, the rotor is such a body). This block is implemented as a user function (an S-function).

Plot result serves for visualizing the rotor temperature field in the course of simulation (the block is implemented as a user function).

Differences extractor is intended for producing signals corresponding to differences of temperatures in the characteristic sections of the rotor.

Differences scope presents temperature differences in form convenient for printing.

Thus, the following has been done as a result of the performed work:

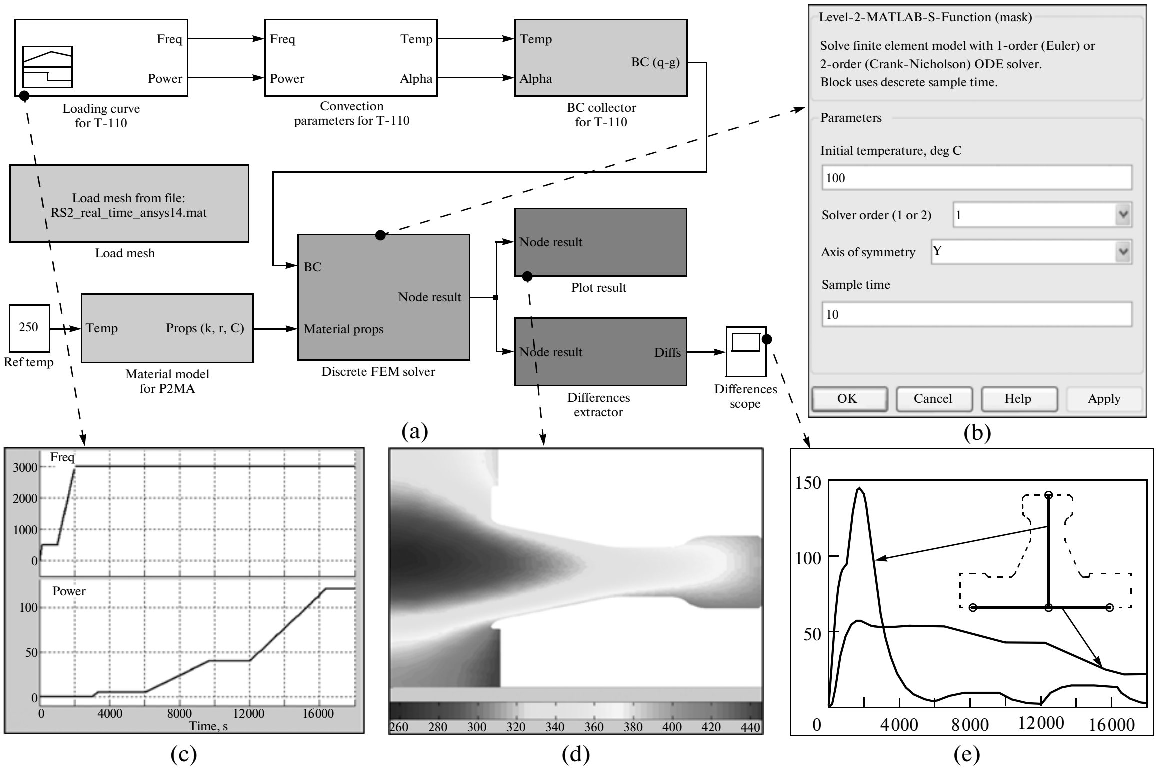


Fig. 6. Dynamic model for heating the control stage of a T-110 steam turbine. (a) Block diagram of the model in the Simulink environment, (b) parameter window of the finite-element model's solver, (c) turbine loading schedules during the startup from cold state, (d) temperature field of the rotor at the time moment 35 min after kicking, and (e) temperature differences at the characteristic sections of the rotor body.

(i) Dynamic models for simulating the heating of parts used in a steam turbine cylinder have been developed with due regard to the possibilities of modern automated process control systems, in which efficient control algorithms are implemented using microprocessor devices.

(ii) It has been found that during startups of cogeneration steam turbines used at CCP-based cogeneration stations equipped with HRBs, the highest temperature stresses arise in the HPC casing.

(iii) A module for calculating temperature stresses in the HPC casing from the input signals received from the regular sensors for measuring metal temperature at the specified points of the casing, and the maximal error of calculating temperature stresses has been determined, which does not exceed 20%.

(iv) It has been shown that the high-pressure rotor can be a critical element during startups of a CCP-based cogeneration station with the parallel process scheme. A dynamic model for heating the critical zone of a rotor suitable for running on a computer with limited capacities has been developed. Solution of an axially symmetrical problem of unsteady heat conductance using the finite element method constitutes the physico-mathematical heart of the model. The error resulting from using the finite element method as a physico-mathematical basis of the model makes 5%.

The obtained results are being used in newly designed and modernized turbines for CCPs produced by the Ural Turbine Works.

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